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Geometrical and electrical characteristics of the initial stage in Florida triggered lightning

J. D. Hill,[1] J. Pilkey,[1] M. A. Uman,[1] D. M. Jordan,[1] W. Rison,[2] and P. R. Krehbiel[3]

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[1] We characterize the geometrical and electrical characteristics of the initial stages of nine Florida triggered lightning discharges using a Lightning Mapping Array (LMA) and measured channel-base currents. We determine initial channel and subsequent branch lengths, average initial channel and branch propagation speeds, and channel-base current at the time of each branch initiation. The channel-base current is found to not change significantly when branching occurs, an unexpected result. The initial stage of Florida triggered lightning typically transitions from vertical to horizontal propagation at altitudes of 3–6 km, near the typical freezing level of 4 km and several kilometers below the expected center of the negative cloud-charge region at 7–8 km. The data presented potentially provide information on thunderstorm electrical and hydrometeor structure and discharge propagation physics. LMA source locations were obtained from VHF sources of positive impulsive currents as small as 10 A, in contrast to expectations found in the literature. **Citation:** Hill, J. D., J. Pilkey, M. A. Uman, D. M. Jordan, W. Rison, and P. R. Krehbiel (2012), Geometrical and electrical characteristics of the initial stage in Florida triggered lightning, *Geophys. Res. Lett.*, *39*, L09807, doi:10.1029/2012GL051932.

1. Introduction

[2] Rocket-and-wire triggering of lightning via a grounded triggering wire, so-called "classical triggering", with negative cloud charge above the triggering site begins with the launching of an upward-propagating positively-charged leader (UPL) from the wire top when the wire top reaches an altitude of typically 200 to 400 m [e.g., *Fieux et al.*, 1978; *Hubert et al.*, 1984; *Biagi et al.*, 2011]. The UPL and the initial continuous current (ICC) that follows presumably propagate toward and into the negative cloud charge. The wire launch, which exhibits wire-top electrical breakdown called precursor current pulses [e.g., *Lalande et al.*, 1998; *Willett et al.*, 1999; *Biagi et al.*, 2009, 2012], the UPL, and the ICC together comprise the initial stage (IS) of the triggered lightning. The transition between the UPL and the ICC is not well defined. Often, after the IS, dart leader/return stroke sequences occur between the negative cloud charge source region and ground, similar to subsequent strokes in natural lightning. In Florida at sea level, the path of the IS, and the other processes that subsequently illuminate the IS's path, generally appear on photographs and to the human eye as a single channel below the cloud base [e.g., *Biagi et al.*, 2009]. On the contrary, photographs of triggered lightning in New Mexico at Langmuir Laboratory at about 3000 m altitude [e.g., *Idone et al.*, 1984] and at St. Privat d'Allier in France at about 1000 m altitude [e.g., *Fieux et al.*, 1978; *Hubert and Mouget*, 1981] typically show an extensively-branched upward positive leader. These visual differences have long been a subject of discussion among researchers. Cloud bases in New Mexico in summer are typically 4 to 4.5 km above sea level, but only 1 to 1.5 km above the level of Langmuir Laboratory, while typical cloud bases in Florida in summer are about 1 km (+/−500 m) above sea level. The atmospheric pressure, and likely the temperature and relative humidity, are all generally higher in Florida near sea level than at the higher-altitude triggering sites noted above; and pressure, temperature, and humidity may well influence the height and degree of IS branching.

[3] In this paper we examine the channel shape and branch characteristics of the IS in nine lightning flashes that were classically triggered at the International Center for Lightning Research and Testing (ICLRT) at Camp Blanding Army National Guard Base in north-central Florida during summer 2011. We map the IS channel(s) in three-dimensions via the TOA locations of positive polarity VHF sources associated with leader tip breakdown obtained from a local Lightning Mapping Array (LMA) [e.g., *Rison et al.*, 1999; *Krehbiel et al.*, 2000; *Thomas et al.*, 2004], with seven LMA sites arrayed in a 10 km radius around the ICLRT. The current during the IS is measured at the lightning channel base. We provide statistics on the IS branching processes: the initial height of the branches, the current at ground when branches are initiated, and the three dimensional propagation speed and overall length of the initial UPL channel and IS branches. We show that upward IS branching at the ICLRT is common above about 580 m but is generally obscured from view by the overhead cloud whose visible base is typically near 1 km and that initially-vertical IS channels generally turn horizontal between 3 and 6 km altitude, near the freezing level of 4 km. Finally, we compare the geometrical characteristics of the IS to those obtained by *Yoshida et al.* [2010] who used two-station VHF interferometric measurements to study two triggered lightning events at the ICLRT in 2009.

2. Experiment

[4] The instrumentation for studying triggered lightning at the ICLRT during summer 2011 consisted of about

[1]Department of Electrical and Computer Engineering, University of Florida, Gainesville, Florida, USA.
[2]Electrical Engineering Department, New Mexico Institute of Mining and Technology, Socorro, New Mexico, USA.
[3]Physics Department, New Mexico Institute of Mining and Technology, Socorro, New Mexico, USA.

Corresponding author: J. D. Hill, Department of Electrical and Computer Engineering, University of Florida, 215 Larsen Hall, Gainesville, FL 32611, USA. (gators15@ufl.edu)

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Table 1. Distance and Azimuth Angle From the ICLRT Launching Facility to Each LMA Station

Measurement	Distance From Launcher (m)	Azimuth (degrees)
LMA Site 1	461	64
LMA Site 2	2988	277
LMA Site 3	2773	134
LMA Site 4	5396	188
LMA Site 5	7701	357
LMA Site 6	5535	296
LMA Site 7	9608	252

90 individual measurements of the lightning electric field, magnetic field, optical, and energetic radiation emissions in addition to an extensive array of cameras. The measurements were arrayed around the launching facility over an area of about 1 km^2. Some of these measurements were used to evaluate the low-altitude accuracy of the LMA source locations. For all triggered lightning flashes, current was directly measured at the lightning channel base in three sensitivity ranges from a few tens of milli-amperes to about 60 kilo-amperes with a 0.001 Ω, non-inductive T&M Research current-viewing-resistor (CVR) with upper bandwidth of 8 MHz. Current waveforms were digitized at 10 MS/s with 12-bit vertical resolution and were bandwidth limited to 3 MHz at the digitizer input. Small fiberglass rockets carrying 700 m spools of 32 AWG kevlar-coated copper wire, the bottom end grounded to the 3 m high metallic launcher, were launched when the quasi-static electric field at ground surpassed a typical threshold of about +5 kV/m (physics sign convention- electric field vector pointing upward toward negative overhead charge).

[5] A seven-station LMA network was operated at the ICLRT during summer 2011, although for all data presented here, only six of the seven stations were operating properly. The LMA stations were arrayed around the launching facility at distances ranging from about 500 m to about 9.6 km. The distances and azimuth angles from the launching facility to each LMA station are provided in Table 1 and shown graphically in Figure 1. Each LMA station recorded the time of the peak power of a received VHF impulse located within the Channel 4 (66–72 MHz) band in consecutive 80 μs time windows. The time-base at each LMA station was provided by an individual GPS receiver. Three dimensional source locations were retrieved using the TOA technique described in Appendix A of *Thomas et al.* [2004]. LMA data used in the analyses are for 5- or 6-station solutions with reduced chi-squared values less than 4, when corrected for the 30 ns actual timing errors of the network.

3. Data and Data Analysis

[6] A total of nine triggered lightning flashes having, at minimum, a full initial-stage were recorded by the LMA during summer 2011. Flash UF 11-32 will be discussed in detail as an example of the nine flashes. Measured

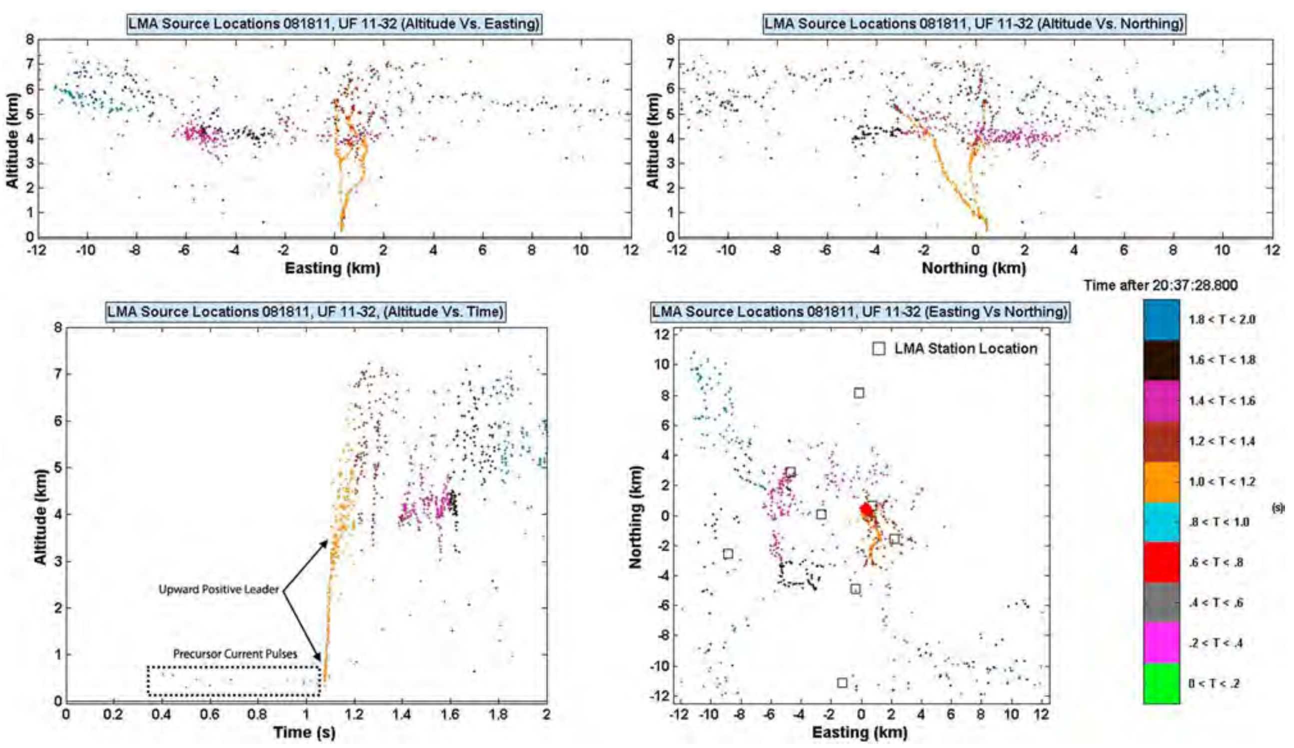

Figure 1. Four projections of the LMA source locations for flash UF 11-32 on August 18, 2011: (top left) an easting versus altitude plot (view looking due north), (top right) a northing versus altitude plot (view looking due west), (bottom left) an altitude versus time plot, and (bottom right) an easting versus northing plot (plan view, launching facility annotated by large red circle). The sources span 2 s in time beginning at 20:37:28.800 (UT) and are color coded according to the key at bottom right, each color corresponding to a 200 ms time window. The times of the LMA sources shown extend only to the time of the end of the IS period, obtained from correlation with channel base current measurements.

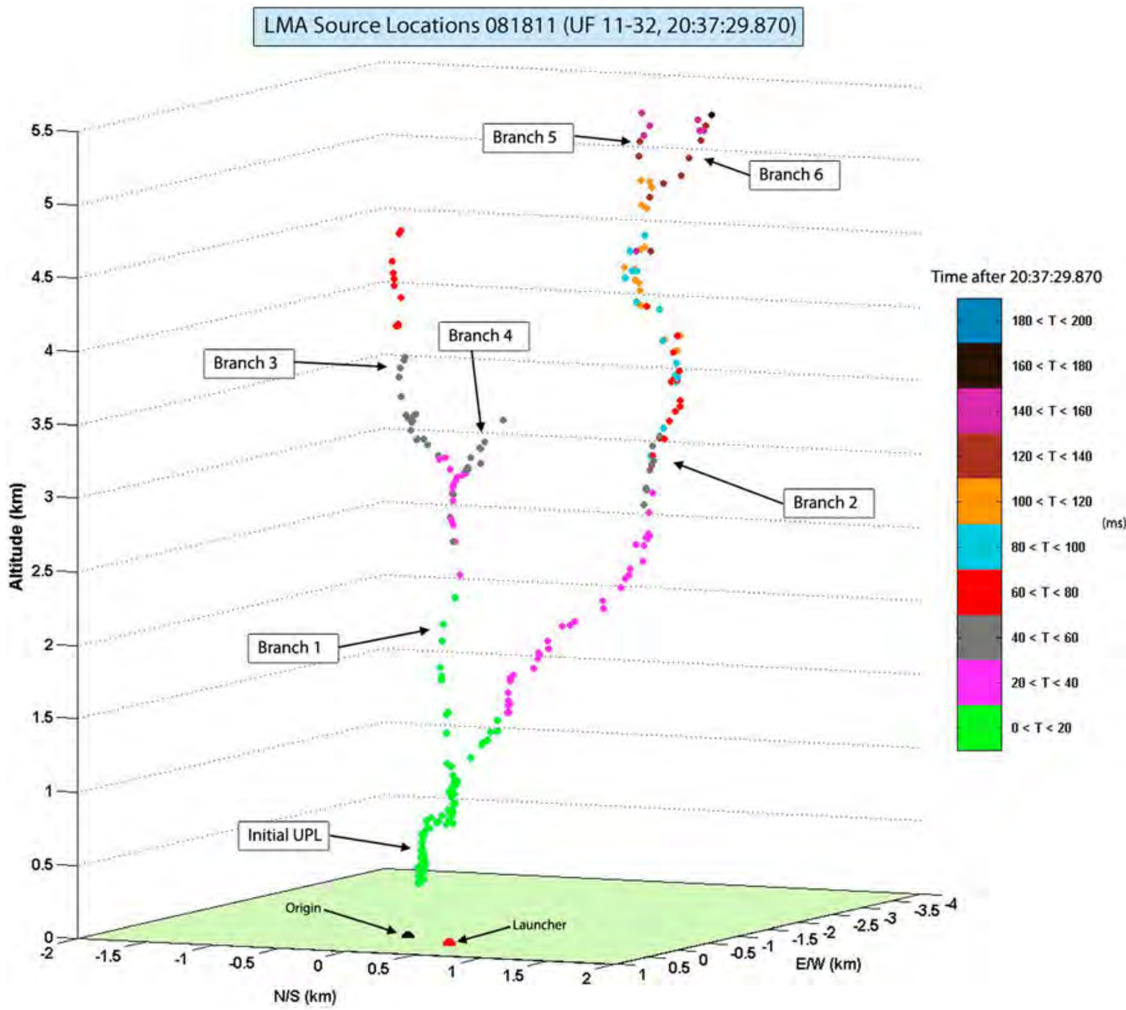

Figure 2. Three-dimensional view of the LMA source locations associated with the sustained UPL/ICC of flash UF 11-32 on August 18, 2011. Sources correlated in time with precursor current pulses and diffuse sources not obviously corresponding to extensions of previous branches have been removed. The sources are color coded in time according to the key at right in 20 ms time windows. The launching facility and coordinate origin are labeled.

geometrical and electrical parameters for the IS are given for all nine flashes.

[7] Flash UF 11-32 was triggered at 20:37:29 (UT) on August 18, 2011 when the quasi-static electric field at ground was about +6.4 kV/m. In Figure 1, four projections of the LMA source locations obtained to the end of the IS are shown. The duration of the wire ascent prior to UPL initiation and the duration of the UPL/ICC were about 1.9 s and 945 ms, respectively. No sources are shown in association with the subsequent leader/return stroke sequences that followed the IS, these data being the subject of a future paper. During the triggering wire ascent and before its destruction, the LMA recorded source locations for 12 VHF sources in time-correlation with positive-polarity precursor current pulses measured at the channel base. These sources are annotated in Figure 1 (bottom left) and occurred over a time period of about 650 ms prior to the initiation of the sustained UPL. The first LMA source corresponding to the initiation of the sustained UPL occurred at an altitude of about 430 m. The UPL is annotated in Figure 1 (bottom left) primarily in orange color and is distinguishable from the preceding precursor pulses by the abrupt change in propagation speed. From independent measurements with ICLRT instrumentation, the wire top at UPL initiation occurred at an altitude of about 280 m. This height discrepancy (the LMA apparently over-estimated the wire-top height by about 150 m) and the altitude scatter of the LMA sources from precursor current pulses in Figure 1 are likely explained by predicted effects of small timing errors in LMA altitude locations of low-altitude sources. For our LMA station locations, and with the closest operating LMA station at about 2.7 km, expected altitude errors are about 100 m for sources at 500 m altitude, decreasing to about 25 m for sources above 2 km, for non noise-contaminated solutions. The altitude errors of any TOA-based system are principally dependent on the ratio of the source height to the distance from the source to the closest sensor [e.g., *Thomas et al.*, 2004].

[8] In Figure 2, a three-dimensional view of the IS is shown on a spatial scale designed to emphasize the upward branching geometry. Only sources corresponding to clearly-defined IS channels are plotted. Sources corresponding to precursor current pulses and sources not obviously associated with the extension of channels plotted in Figure 1 are omitted. There are a total of six clearly defined IS branches

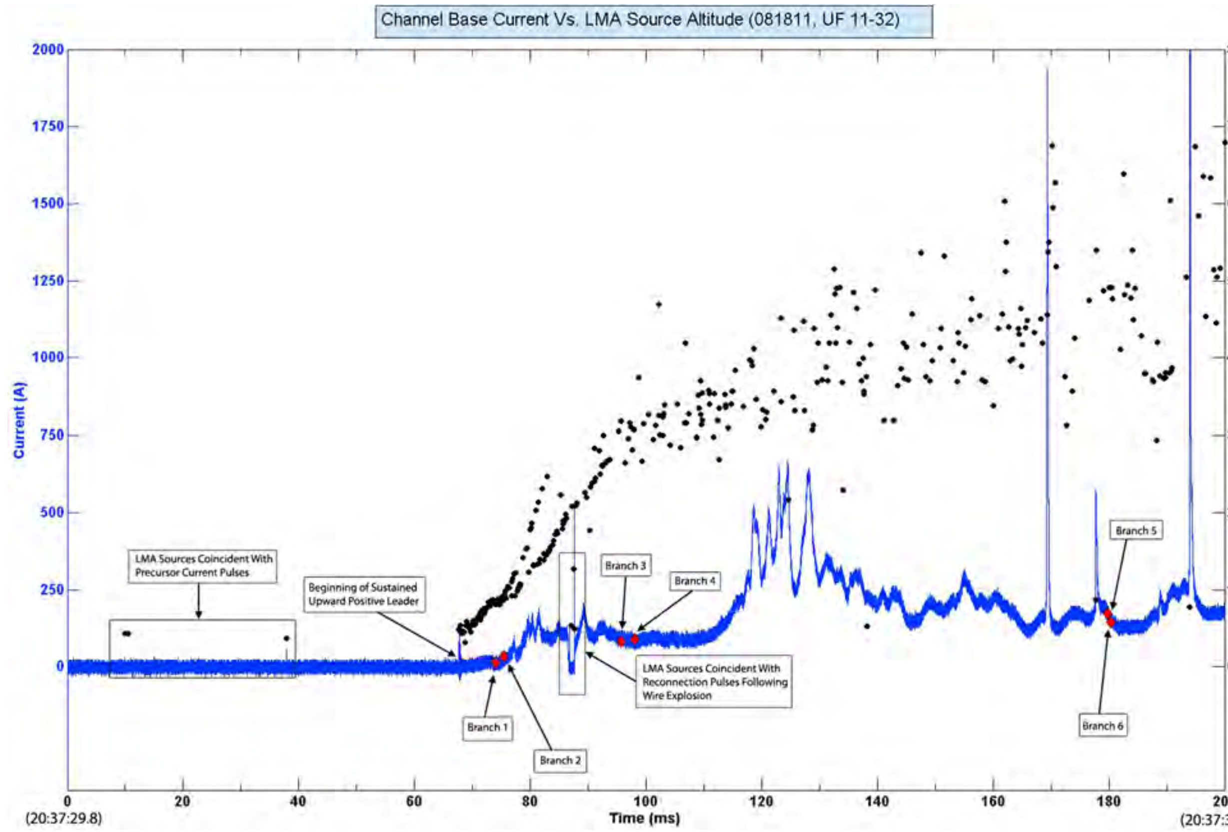

Figure 3. LMA source altitude locations (black points) for flash UF 11-32 overlaid on a 200 ms window of the measured channel-base current. Time zero in this plot corresponds to time equal to 1 s in the altitude versus time projection of the LMA source locations at bottom left in Figure 1. The final 67 ms of the wire ascent and initial 133 ms of the UPL/ICC (total duration of 945 ms) are shown. Sources are annotated corresponding to precursor current pulses and to the reconnection processes following the vaporization of the triggering wire. Red diamonds superimposed on the current waveform indicate the times of the six IS branches shown in Figure 2. The GPS times of endpoints of the time window are annotated below the horizontal axis.

labeled in Figure 2 by increasing initiation time. The sources are color coded in 20 ms time windows according to the key in Figure 2. Estimates for the lengths and average propagation speeds of all branches are calculated by averaging the emission times and three-dimensional spatial locations of the LMA points over time periods of 1–4 ms. The raw data indicate that VHF sources are often emitted from spatial locations well behind the probable tip of the propagating IS channel. As a result, the absolute time progression of the LMA source points cannot be used as a proxy for accurately calculating the length and average speed of the propagating channel. The averaged points are overlaid with the raw data points to insure the channel geometry is not altered significantly and if necessary, the averaging time windows are adjusted accordingly. We estimate the errors in the calculations for overall branch length and average speed to be less than 25%.

[9] The initial UPL (shown in bright green in Figure 2) propagated upward and generally southward for about 630 m at an average speed of about 9.5×10^4 m/s before branching into two distinct IS branches at altitudes of about 880 m (Branch 1) and 870 m (Branch 2) respectively. The two initial IS branches are also clearly visible in Figure 1 (top right), Branch 1 on the right and Branch 2 on the left. Branch 1 propagated generally upward for a distance of about 3.6 km at an average speed of about 9.4×10^4 m/s before splitting into Branch 3 and Branch 4. Likewise, Branch 2 moved generally upward and southward for about 14.7 km at an average speed of about 1.2×10^5 m/s, eventually splitting into Branch 5 and Branch 6. Branch 3 split from Branch 1 at an altitude of about 3.2 km and propagated in an upward and easterly direction for a distance of about 2.1 km at an average speed of about 5.6×10^4 m/s. Branch 4 initiated at an altitude of about 3.1 km and propagated in a northeasterly direction for about 500 m at an average speed of about 3.5×10^4 m/s. Finally, Branch 5 split from Branch 2 at an altitude of about 4.9 km and propagated in a southwesterly direction for 810 m at an average speed of 2.8×10^4 m/s, and Branch 6 initiated at an altitude of 4.8 km and propagated for 770 m in a northwesterly direction at an average speed of 2.0×10^4 m/s.

[10] In Figure 3, 200 ms of the LMA source altitudes (shown in black) are plotted with the measured channel-base current waveform. The corresponding GPS times of the endpoints of the plot are labeled below the horizontal axis. LMA sources corresponding to three precursor current pulses are shown between 10–40 ms in the plot. The sustained UPL is initiated at about 67 ms. The times of the six IS branches are annotated on the current waveform by red diamonds. These branches were initiated

Table 2. Measured Channel-Base Current Parameters for the Duration of the UPL/ICC, 3-D UPL Length From the First Detected LMA Source of the UPL to the First Branch Location, and IS Channel Branching Statistics[a]

		Total UPL/ICC Current Parameters			Initial UPL3-D Length and Average Speed Prior to Channel Branching		IS Branch Geometry and Correlated Current				
Date	Shot	Charge Transfer (C)	Duration (ms)	Average Current (A)	Length (km)	Average Speed (10^4 m/s)	Number of IS Branches	Initiation Altitudes (km)	Lengths (km)	Average Speeds (10^4 m/s)	Initiation Currents (A)
062311	UF 11-11	22	344	64	3.7	13.5	0	-	-	-	-
080511	UF 11-24	46	428	107	12.6[b]	8.4	4	5.2–5.4	5.2–7.2	1.7–3.3	90–125
080511	UF 11-25	28	404	70	0.15	7.9	6	0.75–2.7	1.2–2.4	2.8–7.9	12–60
080511	UF 11-26	120[c]	433	328[c]	0.07	3.8	2	0.58–0.71	2.8–4.1	4.7–18	9–43
081211	UF 11-28	136	694	196	2.5	9.3	3	2.1–2.4	0.81–3.1	4.0–9.3	29–42
081811	UF 11-32	225	945	236	0.63	9.5	6	0.87–4.9	0.51–14.7	2.0–11.9	11–156
081811	UF 11-33	110	630	219	0.81	7.5	6	1.1–5.0	0.82–11.3	4.0–7.5	24–183
081811	UF 11-34	120	567	211	5.0	11.8	3	4.4–4.7	5.0–13.7	2.0–14.8	193–203
081811	UF 11-35	128	726	176	3.7	6.6	2	4.0–4.3	2.1–3.1	3.5–5.9	104–169

[a]Errors in LMA measurements of heights are discussed in Section III. Because of these errors, the 70 m and 150 m UPL lengths and associated speeds at middle in Table 2 are likely underestimated by a factor of 2 to 3.
[b]Prior to branching, the initial UPL of flash UF 11–24 propagated vertically for about 5 km, then turned horizontal and propagated eastward for over 6 km.
[c]Negative charge transport to ground only, although this discharge exhibited a current polarity reversal of 57 ms during the ICC.

with corresponding channel-base current amplitudes ranging from 11 A (Branch 1) to 156 A (Branch 5). Interestingly, there appears to be no correlation between the branching time and any current waveform feature, and the current at ground does not change significantly when branching occurs, an unexpected result. There is likely +/−1–4 ms of error in the placement of the branching times due to the averaging method previously discussed, though accounting for the errors does not appear to significantly alter the above observation. LMA sources enclosed in the black box at about 86 ms correspond to the time of the vaporization of the triggering wire and subsequent reconnection processes [e.g., *Rakov et al.*, 2003; *Olsen et al.*, 2006]. The triggering wire vaporized when the IS was at an altitude of about 2 km. A final observation from Figure 3 is that Branch 1, while having a slightly slower average propagation speed than Branch 2, propagated with higher speed over its first roughly 8 ms. This speed difference is evident in the LMA altitude sources in Figure 3 as the upward splitting of the black data points immediately following in time the red diamond indicating the initiation of Branch 2.

[11] Parameters of the measured channel-base current during the full duration of the UPL/ICC, geometrical characteristics of the initial UPL prior to channel branching, and geometrical characteristics of all IS channel branches are presented in Table 2 both for flash UF 11-32 and the additional eight triggered lightning discharges. The UPL/ICC for flash UF 11-32 was of unusually long duration (about 945 ms) and charge transfer (about 225 C), about three times the duration and about eight times the charge transfer of the typical values reported by *Wang et al.* [1999] (GM duration of 279 ms and GM charge transfer of 27 C) and *Miki et al.* [2005] (GM duration of 305 ms and GM charge transfer of 30.4 C) for triggered lightning discharges at the ICLRT.

[12] The distributions of LMA altitude sources for each of the nine triggered lightning events are given in Figure 4. Source altitudes are not shown above 8 km although they were present for some flashes. For flash UF 11-32 (starred at middle right), the dominant peak occurs at an altitude of about 4 km. This altitude corresponds to the region where the IS begins to diverge from generally vertically-propagating continuous channels into many highly-branched channels that propagate more horizontally. Due to the time resolution of the LMA system (80 μs per source location), these highly-branched channels, many of which are propagating simultaneously, typically appear as broad regions of more diffuse source locations. For the nine events, the peaks of the altitude source distributions are all located between 3–6 km. Lower altitude sources in Figure 4 are attributable to precursor current pulses and upward branching IS channels, statistics for which are provided in Table 2.

4. Discussion

[13] Branching of the IS was observed via the LMA in eight of the nine triggered lightning events, occurring from altitudes as low as 580 m (flash UF 11-26), but more typically from altitudes of about 700 m to 5 km. Due to the low cloud bases, 1 km (+/−500 m) during typical Florida thunderstorms, and the fact that our array of cameras typically views only about 450 m above the launching facility, we rarely view by eye or optically image IS branches. On the basis of work done to date, we have no definitive answer to why there is an apparent difference in branching characteristics between IS's at the ICLRT and at higher-altitude sites.

[14] For two triggered lightning flashes at the ICLRT in 2009, *Yoshida et al.* [2010] used a two-station interferometer to map two IS's from altitudes of 1.1 to 2.4 km and 1.5 to 3.7 km, with three-dimensional velocities of 2.2×10^6 m/s and 3.3×10^6 m/s, respectively. The highest source altitudes of the two recorded IS's were below the typical freezing layer in Florida storms of about 4 km. *Yoshida et al.* [2010] suggest that the cloud charge structure was atypical of a Florida convective thunderstorm and that there may have been a negative charge layer between 2–4 km, similar to that reported by *Stolzenburg et al.* [2002] for mesoscale convective systems. The distributions of LMA altitude sources shown in Figure 4 for our nine triggered flashes, with typical peaks between 3–6 km, suggest that the two events discussed in *Yoshida et al.* [2010] may, in fact, have been

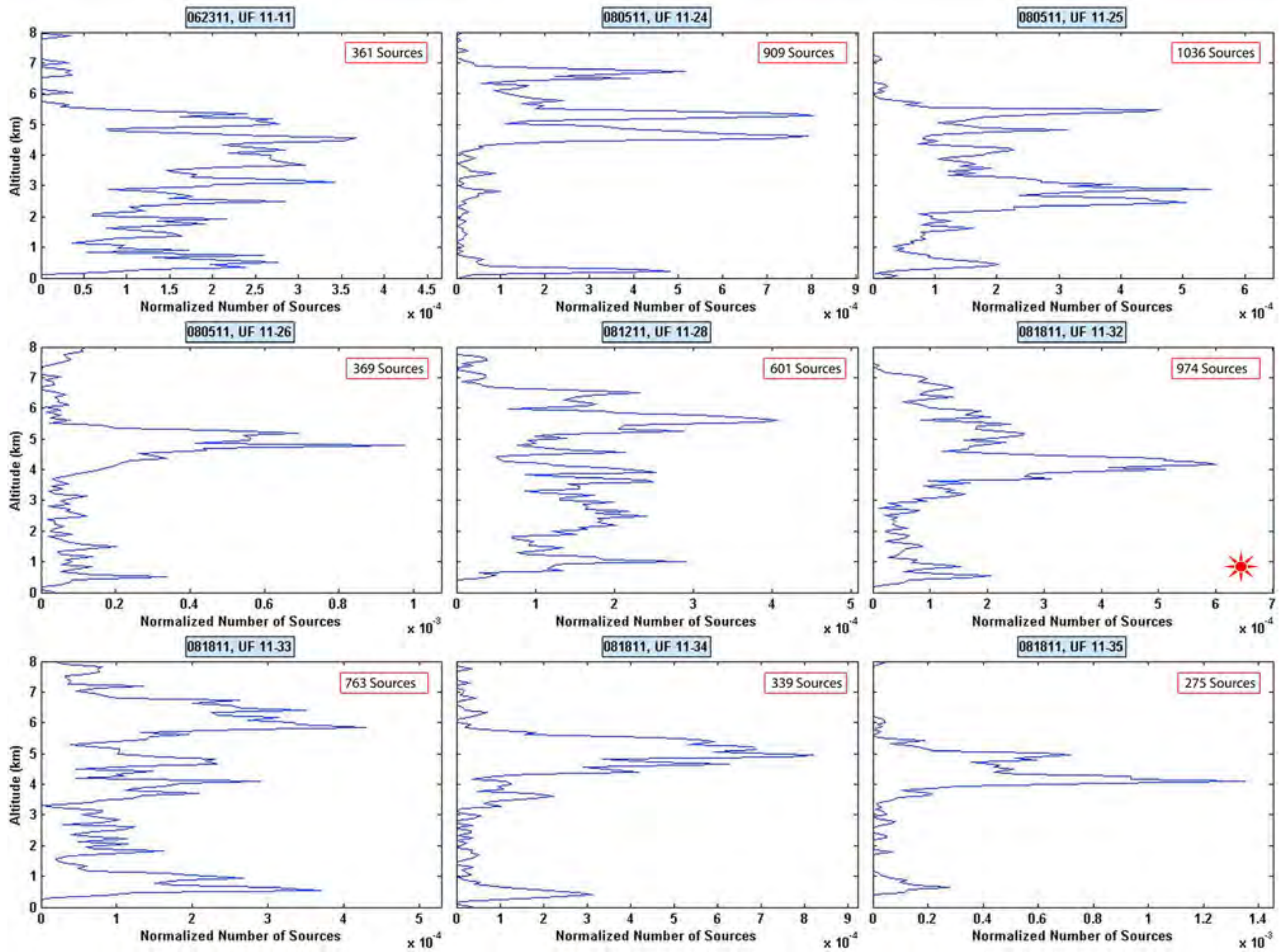

Figure 4. Histograms (bin size equal to 30 sources) of the altitude distributions of LMA sources for nine triggered lightning flashes. Source altitudes below 8 km are plotted. The histograms are derived from sources extending only from the time of the rocket launch through the end of the IS period. The peaks of the histograms are indicative of the altitude region where the IS transitioned from vertical to more horizontal propagation.

typical for Florida thunderstorms. In contrast to the results of *Yoshida et al.* [2010], who reported no sources following the clearly-defined IS channel, the LMA-located sources following the end of the clearly-defined IS channel generally propagated horizontally and outward from the ending point of the IS channel. Often, these areas appear as diffuse sources that gradually progress upward into the probable center of the negative charge region. Further, the average three-dimensional speed calculated for the initial UPLs before any branching occurs (see Table 2) for the nine triggered flashes was about 8.7×10^4 m/s, more than an order of magnitude slower than those calculated by *Yoshida et al.* [2010], and in much better agreement with the two-dimensional UPL speeds of 5.6×10^4 m/s given by *Biagi et al.* [2009] for the first 100 m of propagation of a UPL at the ICLRT, and of 1.0×10^5 m/s given by *Jiang et al.* [2011] for an UPL in China propagating between 130–730 m above ground.

[15] *Yoshida et al.* [2010], based on two triggered lightning events with abnormally large ICC pulses, suggest that positive VHF sources, which have traditionally been thought to have insufficient power to be routinely recorded by VHF imaging systems [e.g., *Shao and Krehbiel*, 1996], can be recorded “if the current is sufficiently high (>1 kA) and/or is impulsive”. The LMA at the ICLRT resolved positive VHF sources from precursor current pulses during the triggering wire ascent with current amplitudes as small as 10 A, with the closest LMA station at about 2.7 km.

[16] Finally, the fact that our IS channels turn horizontal in the 3–6 km range indicates a preferred path for propagation either because of high electric fields there or perhaps because of the characteristics of the hydrometeors present in that range, near the freezing level.

5. Summary

[17] LMA data were recorded for the IS’s of nine triggered lightning flashes. The first branching of the IS was observed in eight of the nine events at altitudes ranging from about 580 m to about 5.2 km. No significant change in the current at ground was observed at the time of branching. For each flash, the IS was observed to transition at 3–6 km altitude, near the freezing level of 4 km, from generally vertically-propagating continuous channels to many highly-branched channels that propagated more horizontally. The LMA resolved VHF sources radiated by positive current impulses with amplitudes as small as 10 A.

[18] **Acknowledgments.** This research was funded by the DARPA NIMBUS program. The LMA system was made available by R. Blakeslee of NASA Marshall Space Flight Center and H. Christian of the University of Alabama-Huntsville. Assistance in the LMA installation was provided by J. Bailey. H. Edens developed important aspects of the LMA processing code.

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